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ACKNOWLEDGEMENTS

Prepared from a script written by Wendy Evans, M.A., for the Glass Technology Gallery at the Science Museum. Design by Alan Jessett, M.I.S.A.

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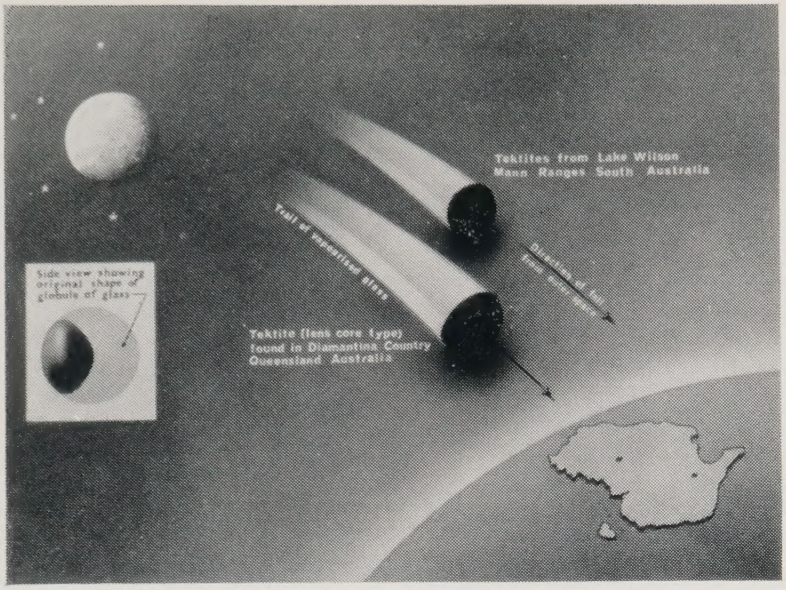

Tektites from Lake Wilson
Mann Ranges South Australia
Trail of expanding gases
Direction of fall from outer space
Side view showing original shape of globule of glass
Tektite (lens core type) found in Diamantina Country Queensland Australia

Natural Glass

Glass from Outer Space

A Tektite is a natural silica glass thought to be of meteoritic origin.

Volcanic Glass

Sudden volcanic eruptions followed by rapid cooling caused highly siliceous lava to form natural glasses of various kinds. Obsidian was used by primitive peoples to fashion into tools and weapons.

Pumice

A natural foamed glass caused by gases being liberated from solution in the lava before and during rapid cooling.

Fulgurite

Produced in certain conditions by lightning striking a metallic ore through loose sand which then fuses.

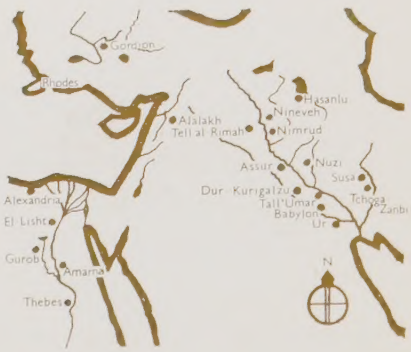
Obsidian Arrowhead

Early Man-made Glasses

It is believed that glass was first made by man in the Near East. Glass was regarded as a substitute for semi-precious stones.

From about 4000 B.C.

The glaze used in Egypt and Mesopotamia to coat steatite and sintered quartz beads and other small objects had affinities with glass. There is glass terminology on cuneiform tablets dating from the 2nd millennium B.C.



Pre-Roman Glass Sites

A cuneiform tablet from Tall'Umar (Seleucia) on the Tigris gives recipes for glaze.

About 1500 B.C.

Hollow glass vessels were probably first made by covering a core with molten glass and then removing the core, or by hollowing out a lump of glass, as if it were stone, by lapidary techniques. Combed thread decoration was often applied.

Moulding

Small objects were made at a very early date by pressing glass with a clay mould.

Hollow vessels were made in moulds possibly as early as 1500 B.C., perhaps by putting powdered frit (the glass ingredients in the first stage of melting) in the mould and reheating it until it fused.

Cold Cutting

Vessels formed by moulding and covered core techniques were often finished by grinding and polishing.

Cuneiform Tablet from Tall'Umar

Early Glass Furnaces

High temperatures are needed to melt the raw materials for glass.

Early melting was probably done in several stages, the results of each being ground down and reheated to achieve as homogeneous a melt as possible.

Shallow crucibles, supported on refractory drums, seem to have been one of the earliest forms. They are thought to have been used at Tell-el-Amarna in Egypt in the reign of eighteenth dynasty Akhenaton (1375–1358 B.C.)

Glassmaking text on cuneiform tablets from the library of Ashurbanipal in Nineveh (669–626 B.C.) refers to three furnaces:

'Furnace for metal'—for fritting.

'Furnace with a floor of eyes . . . where the workman work'—presumably with the fire underneath.

'Furnace of the arch'—for annealing.

Amphorisk: core technique with combed thread, probably 1st century B.C.

Glass and the Roman Empire

The introduction of the blowing iron, probably by the

first century B.C., led to the development of new techniques and the realization that articles could be made on a large scale.

Near Eastern glassmakers travelled to all parts of the Roman Empire and the European glassmaking tradition was established.

Much of the earliest glassblowing was performed using moulds.

When free blowing developed it made possible the use of various forms of furnace decoration. These might be either self-coloured or in contrasting tones.

Early glasses had been opaque and coloured. Gradually more colourless transparent glass was made. In the first century A.D. glassmakers mastered the art of making transparent glass coloured by intention.

Glass in the Roman Empire

Early Glassmaking in Britain

Glass was probably first made in Britain on a limited scale under the Romans. Traces of furnaces have been found at Wilderspool (near Warrington) and Caistor-by-Norwich.

Glazed windows were in use by the first century A.D. and later were much used in the Northern areas of the Roman Empire.

Mould blown flask with maker's name 'Frontinus'

Ancient Craft

Early glass technology was strictly empirical. It was found that sand and other raw materials from traditional homes of glassmaking gave particularly good results, and such materials were exported all over Europe. The chemical composition of a glass depended on the purity of the raw materials and the judgement of the glassmaker.

The disintegration of the Roman Empire led to the gradual development of local glassmaking traditions in Northern and Southern Europe and the areas under Islam. Later, trade and politics encouraged the cross-fertilization of these traditions and glassmaking became international again.

Roman bottle, 2nd or 3rd century A.D.

Glassmaking in Northern Europe

By the ninth or tenth century A.D. a different kind of glass was beginning to develop. Glass furnaces themselves were situated in forest areas away from towns. Ash from local forest plants and trees (especially bracken and beech) was used as a flux.

This contained potash rather than soda, which was the major constituent of the sea plants burnt by glassmakers in the Southern tradition.

Early glass furnaces, built of stone and brick, seem to have been either rectangular, heated sideways, or round, in several tiers and heated upwards through the centre.

Theophilus describes a rectangular furnace and this shape seems to have been used mostly in Northern European glasshouses.

The tiered round furnace has a fire chamber below, a compartment for the posts level with the blower and a place for annealing at the top. Note the form of the blowing iron and the three-legged stool on which the blower sits. This type of furnace has become associated with the Southern tradition of glassmaking and has been described by several writers on glassmaking in Italy, including Agricola.

The furnaces and methods described by Agricola (1490–1555) in *De Re Metallica* (published Basel, 1556) show the merging of the Northern and Southern traditions.

'Some glass-men have 3 furnaces, others 2, others 1. Those who use 3, cook the materials in the first, re-cook it in the second and in the third cool off the glass vases and other hot articles.'

Until the sixteenth century the main product of Northern European glasshouses was window glass of various kinds.

There were two ways of making window glass. Both utilized the principle of a bubble of glass blown out by the glassblower on the end of a long iron tube (blowing iron).

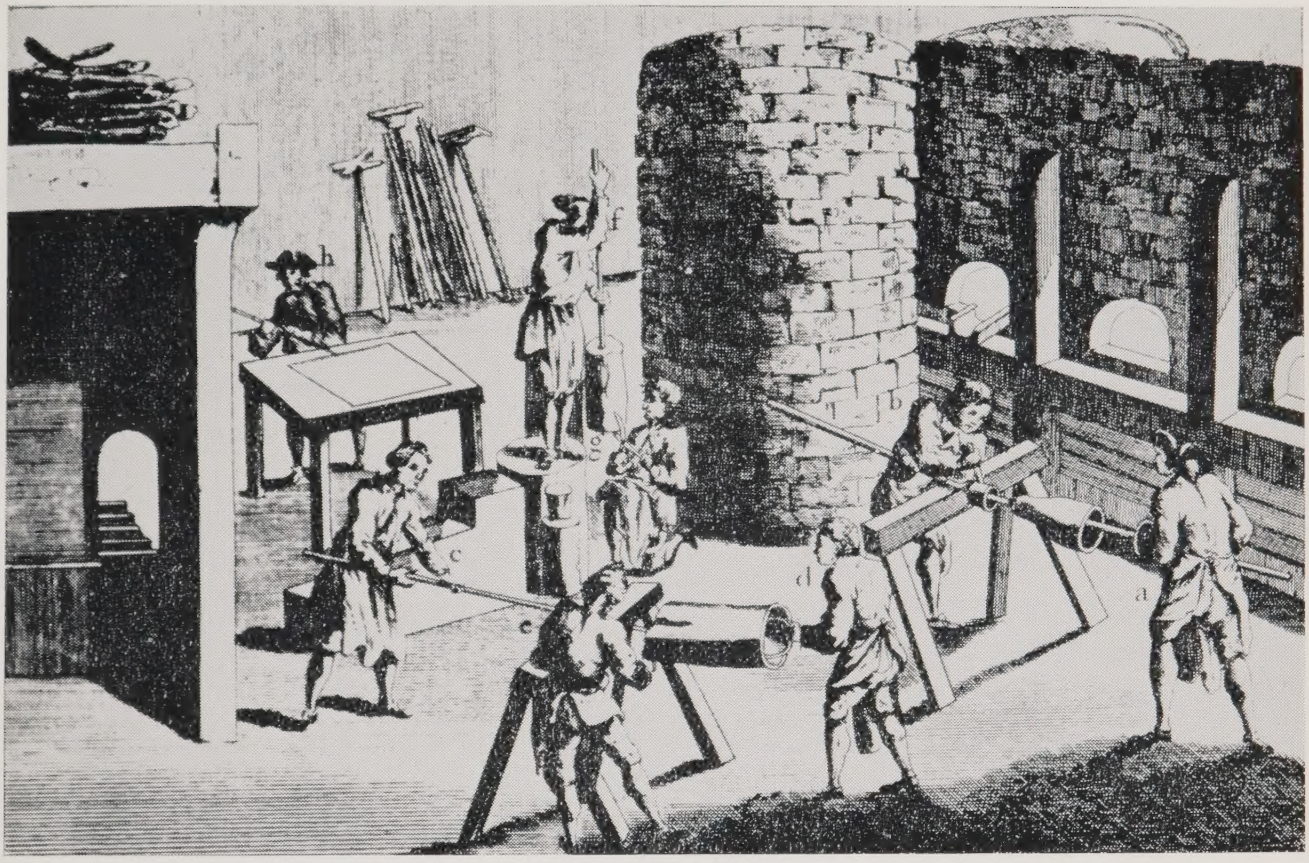
The earliest known illustration of glassblowing (A.D. 1023) from Rabanus Maurus MS.

Glass furnace as described by Agricola

Making Crown Glass: from an 18th century illustration

Crown Glass

This was the speciality of Norman glassmaking families. It is thought that the technique of making window glass



Making Broad Glass : also from an 18th century illustration

by the Crown method was introduced into Britain by the Normans.

Cylinder or Broad Glass

Made by glassmakers in Bohemia and Lorraine and may have been introduced into Britain by the Lorraine glass-makers brought over by Carré in 1567.

Stained and Painted Glass

Glass to make coloured windows was the renowned product of Northern glassmakers, and the beautiful Gothic churches of Northern Europe are a testimony to this.

Syrian enamelled Mosque lamp : early 14th century

Glassmaking in Southern Europe and the Near East

The Near Eastern-Roman glassmaking traditions appear to have continued around the Mediterranean after the fall of the Roman Empire.

Venetian glassmakers gained a reputation for technical skill and this was probably increased by the amount of mystery and strict regulation which surrounded them. They achieved control over many raw materials so that they could produce not only coloured glass but also clear colourless glass known as 'cristallo'.

By the fifteenth century a thriving export trade had been built up. 'Façon de Venise' glass became popular all over Europe. In spite of the fact that personal and trade secrets were jealously guarded, Venetian glassmakers succeeded in escaping and setting up glasshouses throughout Europe.

Venetian Reliquary in Cristallo: 16th century

Glassmaking in Britain

In A.D. 680, according to Bede, Benedict Biscop, Abbot of Wearmouth, County Durham, sent to Gaul for glaziers to work at Jarrow and Wearmouth.

From the thirteenth century A.D. there is evidence of a glass industry in the Weald, the afforested area of Surrey and Sussex around Chiddingfold, which was an industrial zone during the Middle Ages. With probable Anglo-Norman origins the main product seems to have been window glass.

Glass from Chiddingfold was used to glaze the old chapels of St Stephen and St George at Windsor.

Furnaces were probably used for comparatively short periods. In some places glassmaking may have been a seasonal occupation for farmers (as with iron working in the Weald).

Goblet made by Verzelini diamond point engraved

Reorganization of Glassmaking in Britain—Birth of the Modern Glass Industry

The native industry was revitalized by glassmakers from Lorraine and of Italian origin who were brought over by Jean Carré in 1567. He held monopolies to make both window glass (in the Weald) and 'crystal' in imitation of the clear glass of Venice (in London).

1575:

A patent was granted to an Italian, Jacopo Verzelini, to make 'drynkyne glasses such as be accustomablie made

in the town of Murano' and to teach British workers how to make them.

The early glass industry was dependent on ample supplies of cheap wood for fuel. By the late sixteenth century wood was becoming scarce and many industries, including shipbuilding, were competing for it.

This hastened the change to coal-fired furnaces and in 1615 there was a Royal Proclamation forbidding glassmakers to use wood for fuel. The monopoly system continued for some time. These two factors led to the permanent establishment of the glass industry in Britain.

Sources of clay, coal, and convenient transport systems influenced the geographical situation of the permanent glass industry.

In the sixteenth century the trend in chemistry was away from theory and towards utilitarian purposes. It became concerned with new substances useful in medicine and the industrial and decorative arts.

L'Arte Vetraria, by Antonio Neri, published in Florence, 1612, was the first systematic account of the treatment and preparation of raw materials to make glass.

This was translated into English in 1662 by Christopher Merrett, physician and founder-member of the Royal Society. 'The Art of Glass' contained, in addition, Merrett's own 'Observations' on glassmaking practices and furnaces.

The establishment in 1660 of 'The Royal Society of London for further promoting by the authority of experiments the sciences of natural things and of useful arts' played an important part in the story of glassmaking.

Several of the merchants who formed the Worshipful Company of Glass Sellers of London (incorporated in 1664) were also Members of the Royal Society.

The Company supported George Ravenscroft's researches into a 'perticuler sort of Christaline Glasse resembling Rock Christall'. Ravenscroft, attempting to counter the effect of 'crizzling' or clouding of glass caused by fumes from excess of alkali in the batch furnaces, added lead to his raw materials and produced a new type of glass which superseded 'cristallo'. 'Glass

Late 17th century Goblet in lead glass

of lead' had a comparatively long working period. This influenced the styles into which it was fashioned and contrasted with the quick-cooling and more brittle Venetian glass of soda. Lead glass was softer and had a very high refractive index, and both these factors made it particularly suited to cutting and polishing. Above all it enabled the optical sciences to progress.

The Glassmaker's Chair

This distinctive combination of seat and work bench was an early seventeenth century development.

Glassmaker's chair

The first known illustration of a glassmaker's chair is on the frontispiece to the *Ars Vitraria* (Amsterdam 1668). This also shows the beehive-shaped furnace and the long annealing lehr running off it.

Glassmakers' tools: from Ars Vitraria 1668

Alchemist's laboratory 17th century, showing glass apparatus. After Teniers

Tools were made of metal and wood and were similar to those used today.

Glass in Science

Glass vessels had been used in laboratories since early Egyptian times.

From mediaeval times improvements in glass working and in glass itself have provided the opportunity for almost all major scientific discoveries outside mathematics.

Increased skill in the manipulation of hot glass tubing led to the manufacture of instruments which enabled scientists to establish the concept of a gas.

Among the earliest thermometers were those made and used at the Academia del Cimento at Florence. These were followed by barometers and all the instruments employed in vacuum science.

17th century Florentine thermometer as made at the Academia del Cimento

Optical Glass

Convex spectacles were in use in North Italy from the

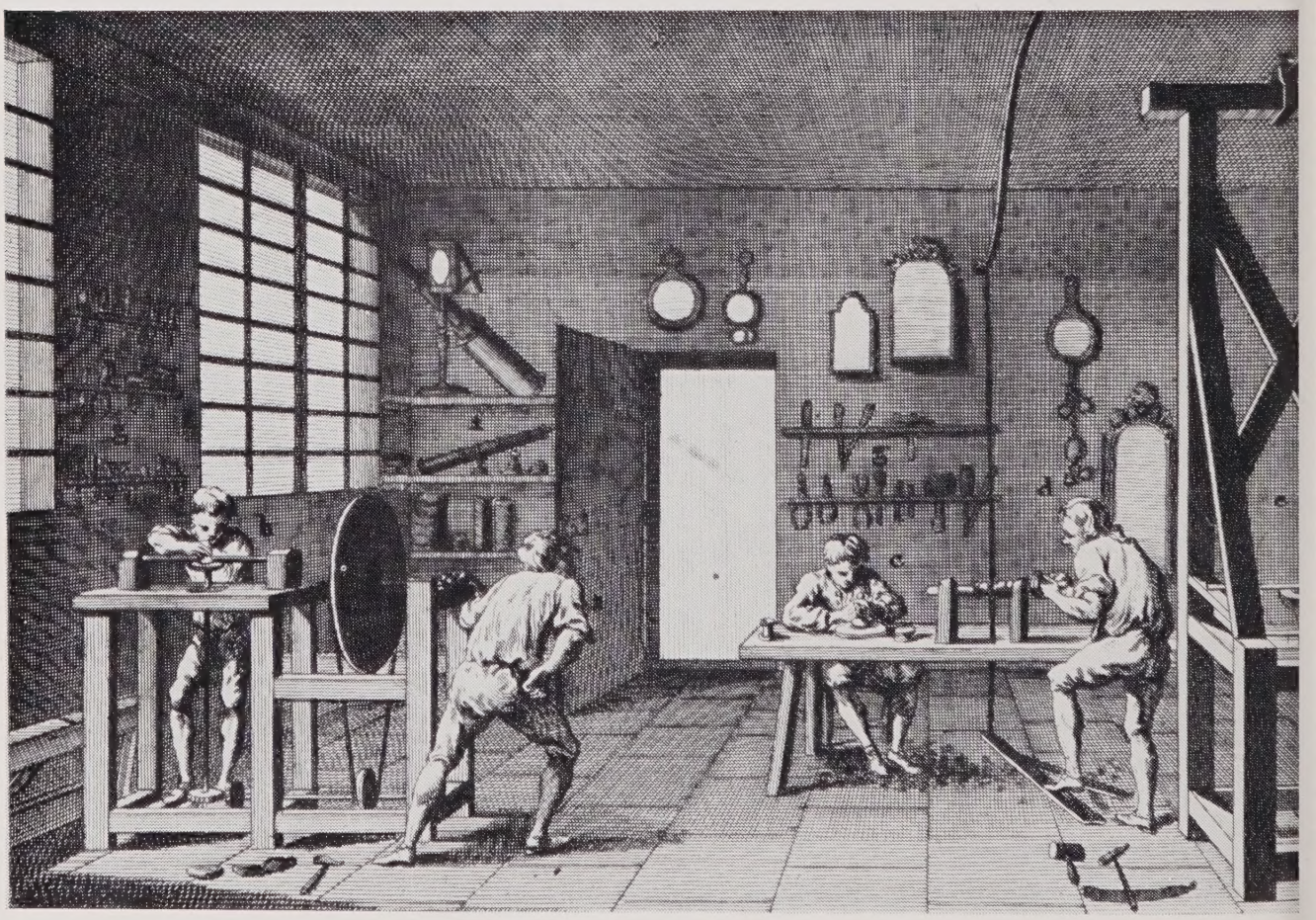
late thirteenth century but concave lenses were not in general use until the mid-sixteenth century. The combination of convex and concave lenses led to the invention of the telescope.

Newton, in 1671, found that the prismatic colours of the glass led to chromatic aberration and the problems of reflection and refraction of light. In 1729, Chester Moor Hall and later John Dollond (1758) found that by combining convex and concave lenses of suitable refractive indices—a lead glass negative lens and a soda-lime positive lens—a composite lens could be made which gave refraction without colour. These were the first achromatic lenses.

Among the largest mirrors for astronomical telescopes were those made by Herschel, who, in 1789, produced one with a focal length of 40 ft and 4 ft diameter.

In 1798, Pierre Louis Guinand, a Swiss, first used a stirring device in the manufacture of optical glass which

Grinding Optical Glass: 18th century. From Diderot's 'Encyclopédie'



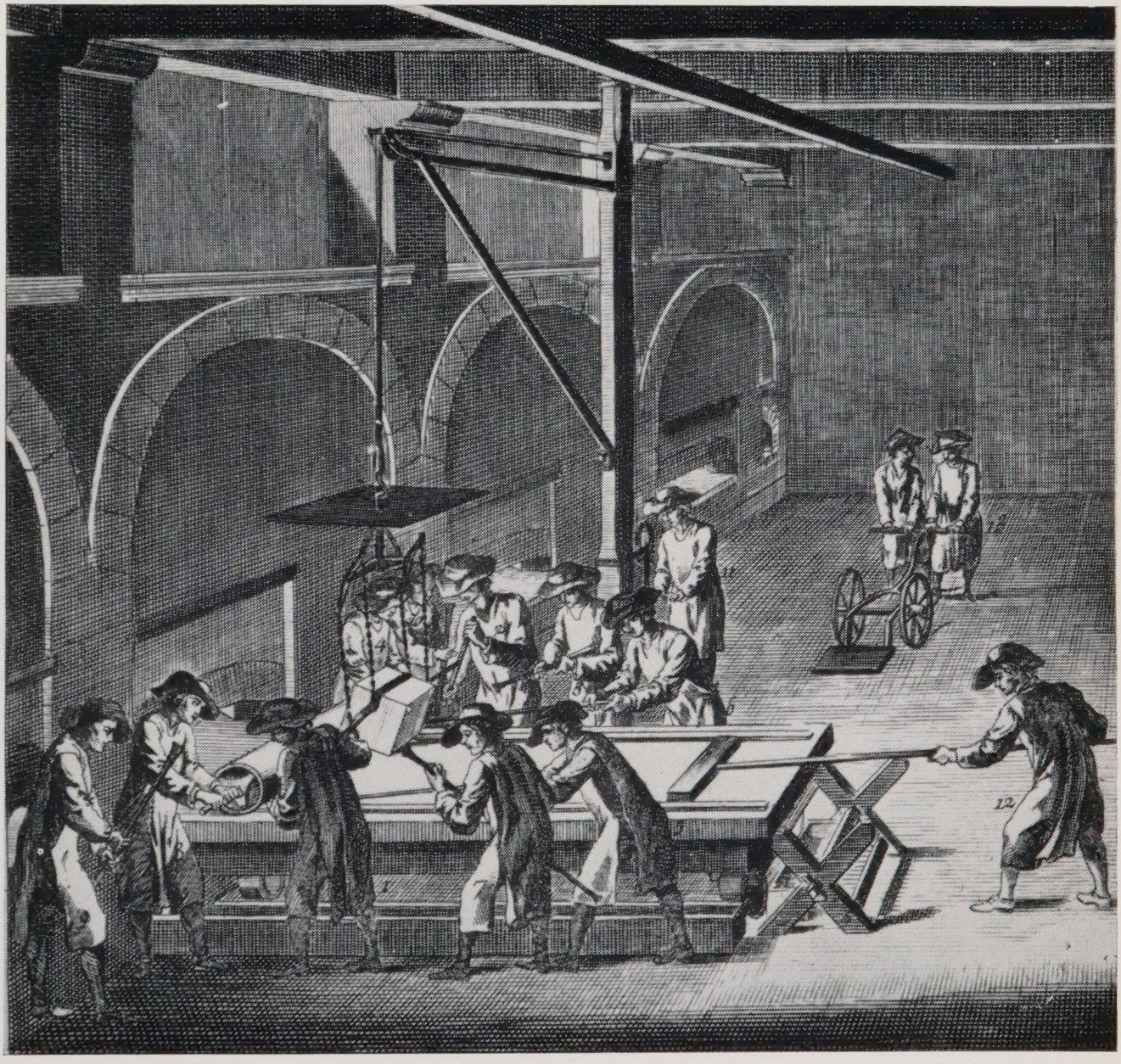
improved its homogeneity. The use of heavier materials extended the possible range of compositions for optical glasses.

Cast Plate Glass

By the mid-seventeenth century there was a great demand for large sheets of clear glass for mirrors and coach doors. Special works were set up in Britain and France and Italian workers brought over to work in them.

In casting plates of glass by the French method, the small crucible was brought from the furnace to the cast-

Casting Plate Glass: 18th century. From Diderot's 'Encyclopédie'



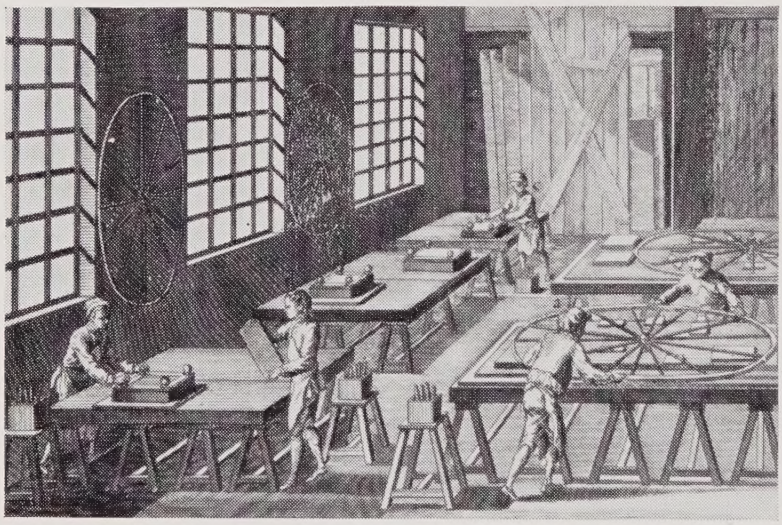
ing table. After skimming, it was tipped up and rolled out and the flat plate was pushed into the annealing lehr.

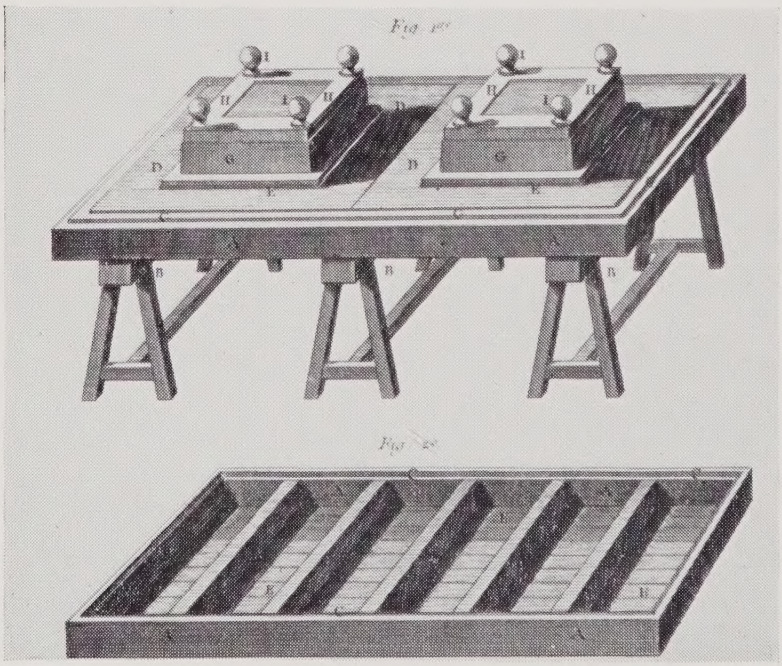
Grinding the plates of glass manually

Note in picture below the small plates being hand ground on the side trestles and the manually operated wheel which was attached to grinding stones for grinding the large plate.

The method of making plates of high quality glass by casting was not introduced into Britain until the British Cast Plate Glass Co. was established at Ravenhead, St Helens, Lancs., in 1773.

Early mirrors were made from the polished surface of





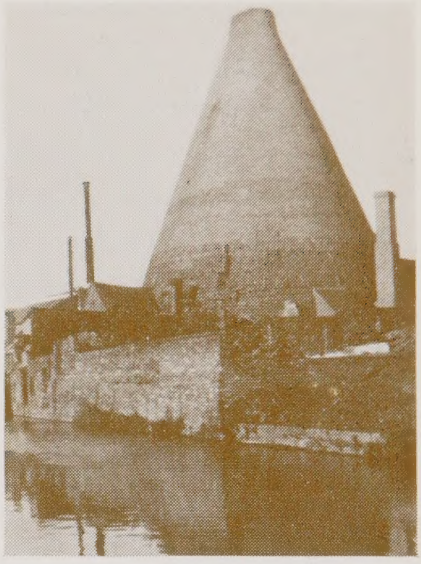
Grinding Cast Glass: 18th century. From Diderot's 'Encyclopédie'

metal or stone. Glass, with a back coating, was used for mirrors in Venice in the fourteenth century.

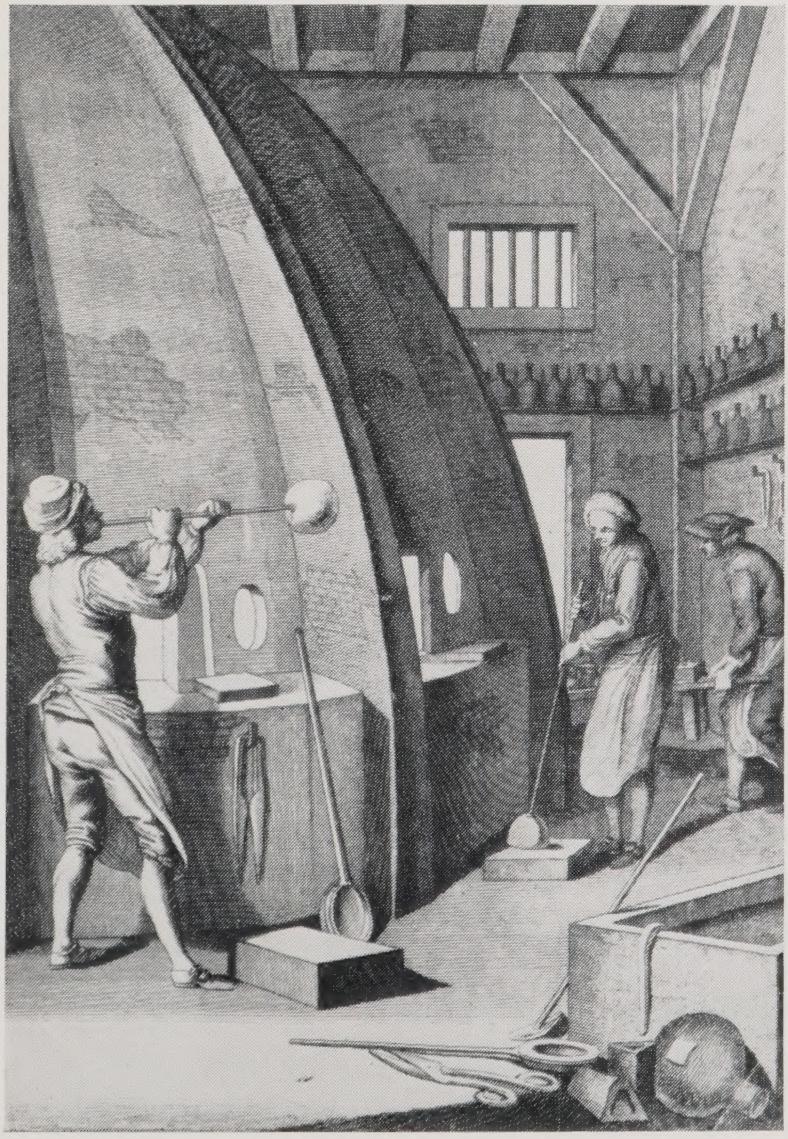
The making of mirrors was not introduced into Britain until the early seventeenth century.

The glass cone was an English invention of the seventeenth century. The cone-shaped building housed the furnace and the glasshouse, and acted as a chimney which made heating more efficient and created cooler working conditions.

Covered glass pots may have evolved from the melting of lead crystal glass which would have been harmed by the sulphur compounds present when coal was burned. Open pots continued to be used for bottle and window glass production.

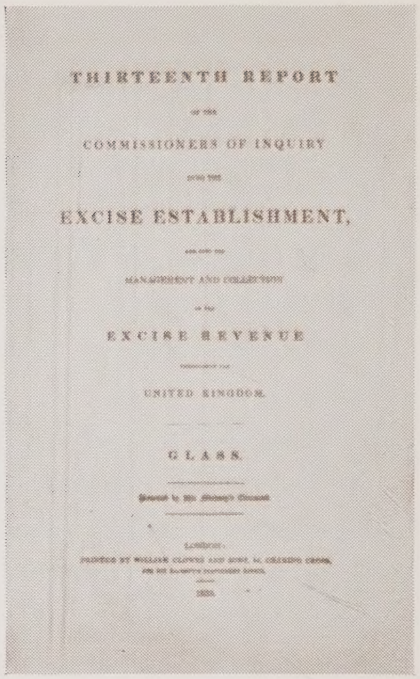


Glass Cone



Blowing bottles by hand

Early Glass Containers


THIRTEENTH REPORT
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GLASS.

The export to Europe of large quantities of hard paste porcelain from China in the eighteenth century led to many attempts at imitation including opaque white glass, made in porcelain shapes and decorated by painting.

Glass bottles replaced stoneware for conserving wine and ale by the middle of the seventeenth century. Bottles were made by the mouth-blowing technique and were surprisingly consistent in their capacities.

The lost art of allowing vintage wines to mature in air-tight containers was rediscovered in the eighteenth century when glass could be completely sealed with cork. Bottles became long and cylindrical so that they could be stacked horizontally.

In 1804 Nicholas Appert, a Parisian confectioner, developed a method for preserving food in glass jars. In 1821 Ricketts patented a mould for blowing bottles which increased speed and uniformity of production.

Effects of Taxation

Excise duties on the amount of glass melted in a glasshouse were levied continuously from 1745 to 1845. There were five categories of glass manufacture recognized: crown, broad or spread (inferior window glass), flint, bottle, and plate. Only one kind was allowed to be melted in one glasshouse. Excise officers were on duty in every glasshouse checking all operations. All glass had to be accounted for. The Acts had generally inhibited the progress of glass manufacture technology.

When the Free Trade Act with Ireland was passed in 1780, many English glasshouses set up in Ireland to continue their work there. In 1825, Excise Acts were enforced in Ireland and the glass industry died out.

The inquiry of the Excise Commissioners in 1835 led to the eventual repeal of the Acts in 1845.

Modern Industry

Joseph Paxton's Crystal Palace for the Great Exhibition of 1851 marks the beginning of the discovery of glass as a new material. This attractive and functional edifice en-

couraged the use of glass in public, domestic, and horticultural building.

In 1860 F. & W. Siemens' regenerative furnace using producer gas was first used in a glassworks. The higher temperatures produced shortened the life of the fireclay melting pots.

By 1870 the first Siemens' regenerative tank furnace was in operation.

The Crystal fountain

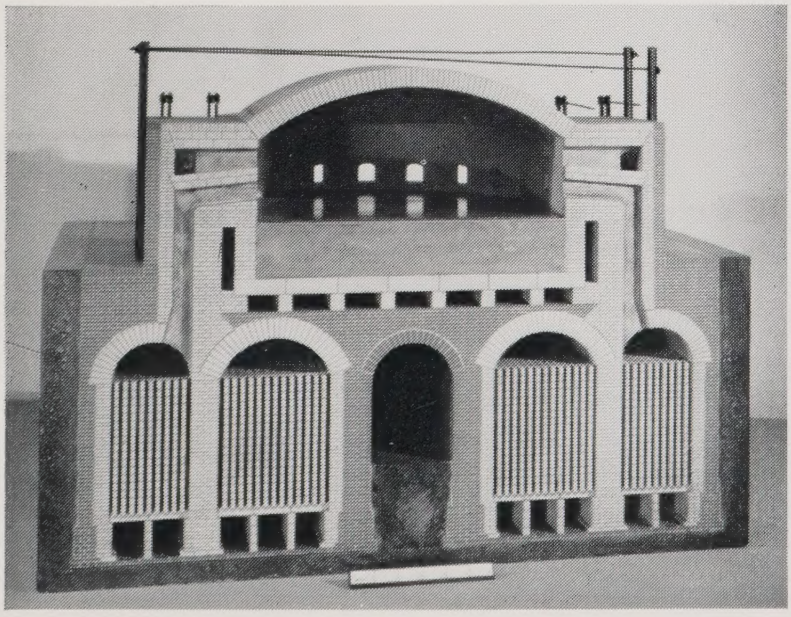
New Glasses for Science and Industry

The increasing demands of the optical industry for new glasses of controlled refractive index and dispersion (for more complex lens systems) and the improved supply of pure chemicals from the chemical industry led to the detailed study of existing glasses and the development of many new ones.

Otto Schott related glass to his other pyrochemical studies and realized that the behaviour of a glass was more fundamental than its specific composition. This enabled him to use rare earths and metallic oxides to develop many completely new optical glasses with Ernest Abbe (from 1882).

They produced heat resistant borosilicate glasses for thermometers which would also withstand chemical attack.

Borosilicate glass was used for the world's largest



Model of Siemens' regenerative tank furnace

piece of glass—the 200 in. telescope mirror at the Mount Palomar Observatory, 1934.

1889:

Professor C. V. Boys used quartz fibres in torsion balances to successfully determine the weight of the earth.

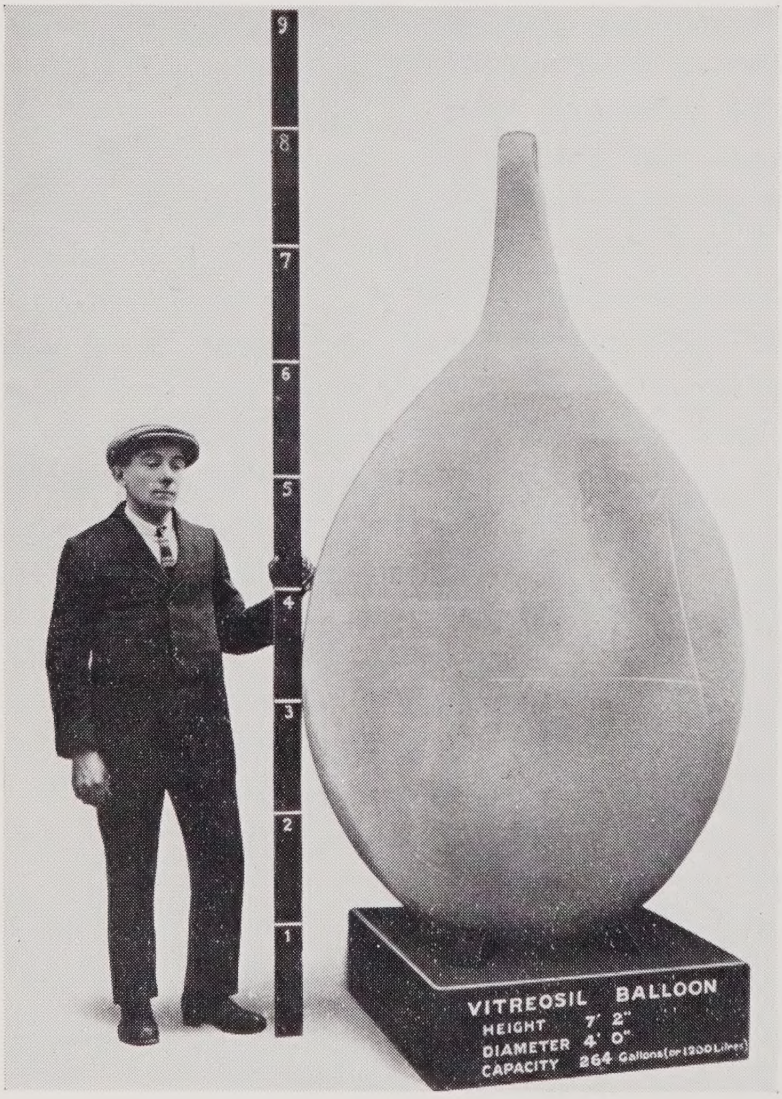
1904:

First commercial production of fused silica.

1915:

The world's first university department of Glass Technology was set up in the University of Sheffield.

Largely due to the work of Dr (later Professor) W. E. S. Turner who had begun to apply physical chemistry to the problems of metallurgy, a Scientific Advisory Committee was set up by the University to cope with the technical



Pure fused silica balloon flask made in 1924

problems of war production and it was realized that an opportunity existed for introducing science into all sections of the glass industry.

1927:

J. L. Baird discovered that assemblies of glass rods could be used to convey pictures.

This was later developed in 1954 into the science of fibre optics.

Many special glasses and glass-to-metal seals have been developed for vacuum electronic devices which use many gases and exert high pressures.

Silicate glasses do not resist sodium vapour so a non-silica glass made from boric oxide, barium oxide, aluminium oxide, and magnesium oxide has been developed for the inner surface of the tube.

1947:

Introduction of photosensitive glass.

Glass containing certain metals (e.g. gold) when exposed to UV radiation will form a latent image which can be developed by heat treatment.

A photographic negative will produce a print which is transparent, 3-dimensional, and permanently part of the glass.

1957:

Development of glass ceramics meant a new range of materials became available.

Work on photosensitive glass showed that if further

Glass ceramics, developed for rocket nose cones now have industrial and domestic uses

crystals are precipitated and the glass is then heated to a high temperature it does not melt but forms an opaque polycrystalline ceramic with high mechanical strength and improved electrical insulation qualities.

Mass Production of Glass Containers

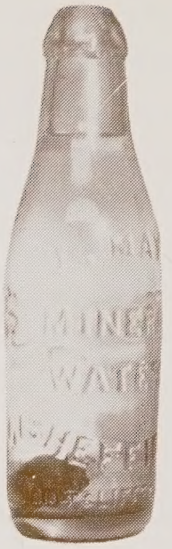
1870:

Reorganization in bottle factories led to the increase in average daily output per blower from 40 to 300 dozen per day.

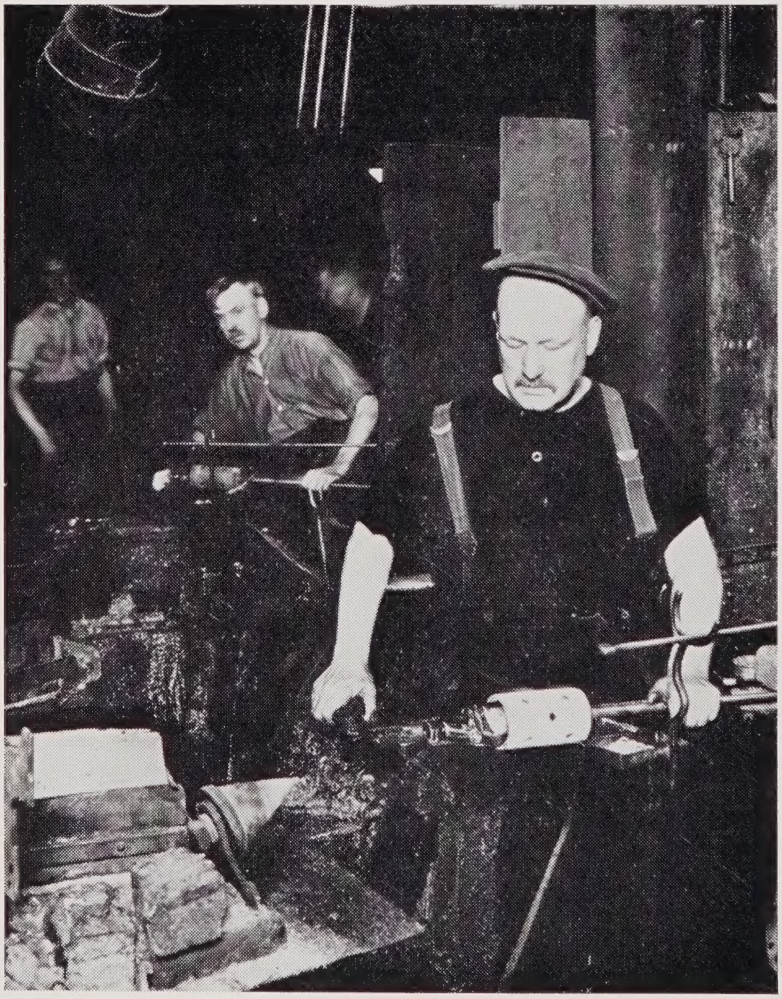
1887:

The first machine to successfully produce bottles semi-automatically—the Ashley machine—was in operation in Castleford, Yorkshire. Two men working an Ashley machine could produce 200 bottles in an hour.

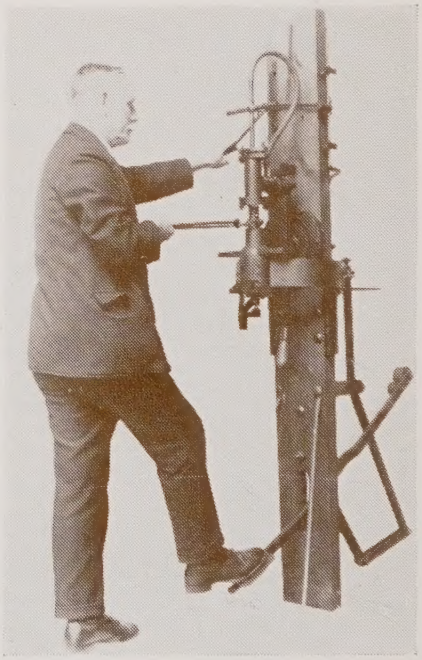
Efforts at producing a mechanism to feed glass automatically from the furnace began in the 1880's.



Mineral water bottle with internal glass stopper, 1875



Manufacture of hand-made bottles



Bottle making on the Ashley machine

1901:

Homer Brooke produced the first successful feeder device.

1907:

Bottles were first produced automatically in Europe (Manchester) on a machine invented by Michael Owens.

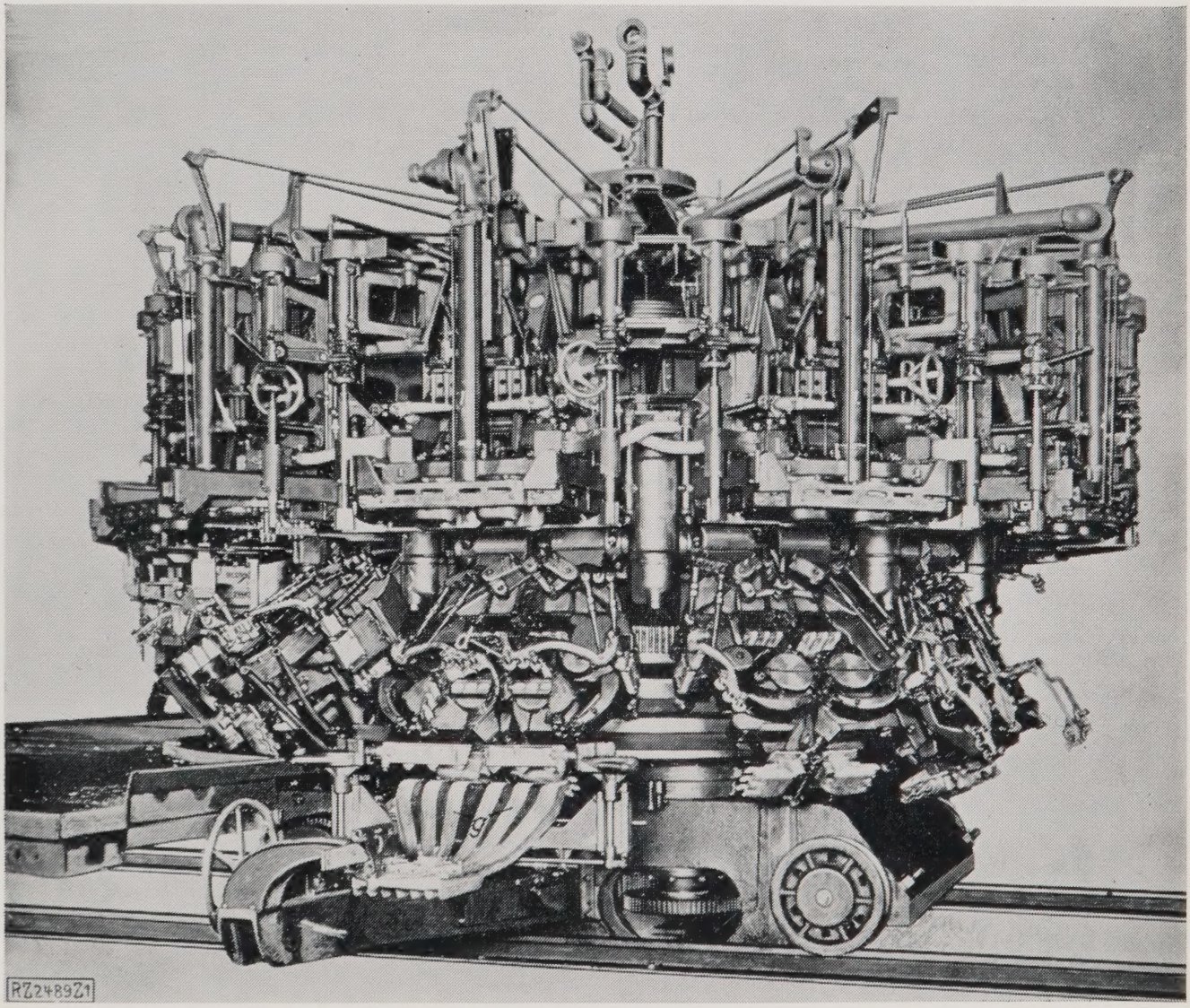
Glass was fed from the furnace into a revolving pot from which an exact amount was sucked up into revolving parison moulds and transferred to finishing moulds.

A ten-head Owens machine produced highly accurate bottles at the rate of 2,500 per hour.

1918:

Commercial development of Peiler's automatic 'gob' feeder device to deliver glass of predetermined size, weight, shape, and temperature to the forming machine.

Owens' Machine



1925:

Invention of the I.S. machine for the automatic production of glass containers by Henry Ingle.

Instead of a rotating machine, gathers of glass are conveyed from the feeder by a shute to stationary moulds in each individual section. While one parison is being blown, the next one is being formed.

Developments in Flat Glass

1870:

Chance Brothers introduced double-rolled cathedral glass using patterned rollers. By varying the surface of the rollers different textures and degrees of translucency could be obtained. Before this all coloured flat glass had been blown and was transparent.

1898:

Wired glass was first manufactured commercially.

It was a safety glass but not, as had first been thought, a new strong material like reinforced concrete. Initially there were problems in finding a suitable wire.

As with glass containers and tubing, early attempts to make flat glass by machine sought to mechanize hand processes.

1910:

Introduction into Britain of the Lubbers' machine-drawn cylinder process for making sheet glass.

1913:

First commercial operation of the Fourcault process for drawing flat sheets of glass directly from the furnace.

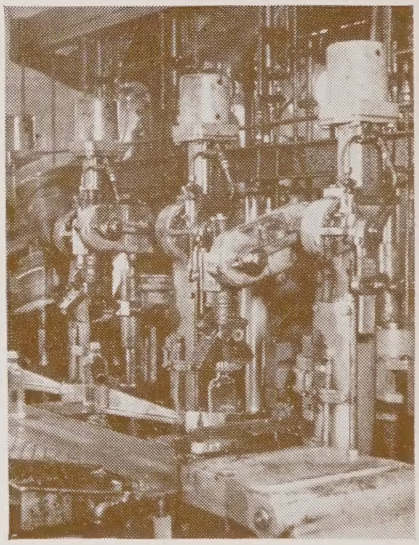
1918:

Bicheroux developed de Nehou's process for making plate glass (1688) by casting the molten glass between rollers down a slope on to a series of moving tables.

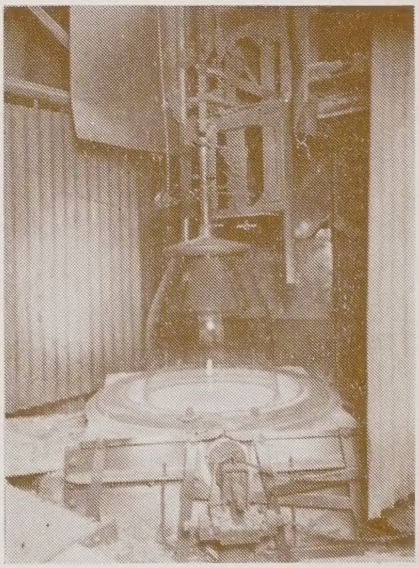
1923:

The Ford process (developed in conjunction with Pilkington Brothers Ltd) for the continuous rolling of narrow widths of glass (for windscreens) went into operation.

The glass was melted in a tank furnace and fed between two rollers straight through to the annealing lehr.



Finished bottles automatically lifted from I.S. machine on to conveyor belt



Making sheet glass by the drawn cylinder process

Casting plate glass by the Bicheroux method

It was ground and polished (one side at a time) by the Pilkington continuous grinding and polishing process.

1937:

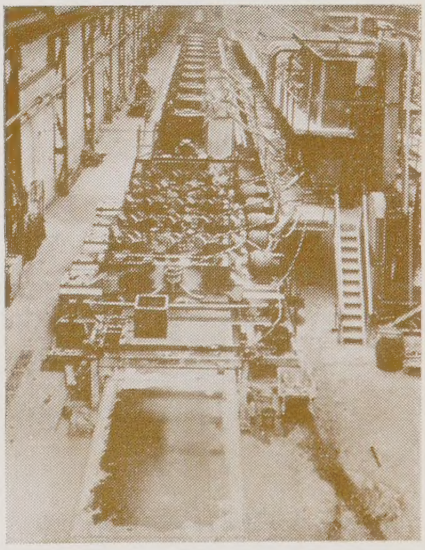
Introduction of the Pilkington continuous rolling, twin grinding, and polishing process for making plate glass. Both sides could be ground and polished simultaneously.

1958:

Continuous process for making optical glass introduced into the United Kingdom.

1959:

Glass produced by the Float Glass Process for the continuous manufacture of flat glass of a high surface quality without grinding and polishing.



Continuous grinding and polishing plate glass by the Pilkington Method

Glass Tubing

1896:

Houghton mechanized the manual method of drawing tubing.

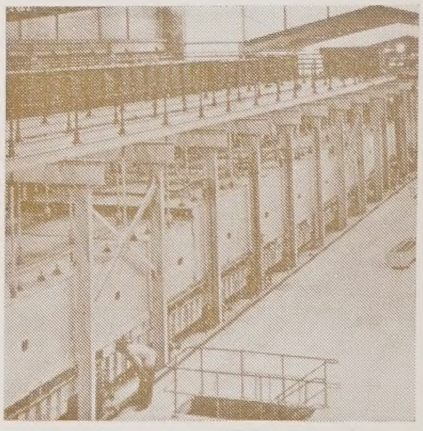
Glass tubing automatically drawn on a Danner machine

The molten glass was gathered on an iron from the pot and drawn up a tower.

1917:

Charles Danner introduced the first method for drawing tubing continuously. Molten glass flowed down from the tank on to a hollow clay mandrel and the tubing was drawn off to the cutters on rollers.

Subsequent methods have been developed on the same principle.



The Float Glass process is dependent on absolute control of ambient temperature and atmosphere

Glass Fibre

1908:

The first Gossler process for producing glass fibres.

Cullet was melted and flowed through a perforated disc and the fibres were wound on to a drum. This was similar to the hand methods used by nineteenth-century itinerant glassblowers.

1930 :

A drum-wound process was introduced into England for making glass fibres for heat insulation.

1931 :

Centrifugal force used as a means of drawing fibres in the Hager process.

1938 :

Electric melting was used in the continuous filament process.

1939 :

Steam blower used to manufacture glass wool—the length of the fibre depending on the speed and turbulence of the steam.

Shows by glass workers were popular 19th century entertainment

Glass in Vacuum Science

1879 :

First electric light bulbs produced for Edison (U.S.) and Swan (G.B.).

A transparent vacuum tight envelope was required to prevent oxygen and water vapour from the atmosphere reacting with the hot filament.

1892 :

Dewar invented a double-walled glass vacuum bottle to keep liquid gases cold.

1904 :

The domestic vacuum flask was first produced by Burger.

1917 :

Introduction of the Westlake Automatic Electric Bulb Machine.

Based on the Owens Machine, it is a continuous rotation one-table unit.

1926 :

Invention of the Corning Ribbon Machine for the automatic blowing of electric light bulbs.

It is the fastest automatic glass forming machine yet

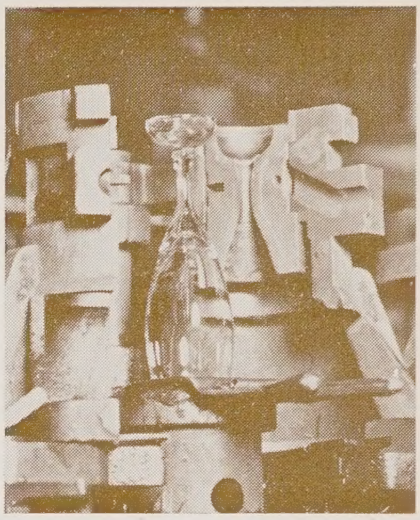
Edison's original incandescent electric lamp, 1880

built. Original production was 400 per minute. This rose to over 1,000 per minute.

1948:

Cathode ray tubes produced automatically in the United Kingdom.

The three parts—face plate, funnel, and neck—are made of different glasses. An even thickness must be maintained to withstand internal pressures.



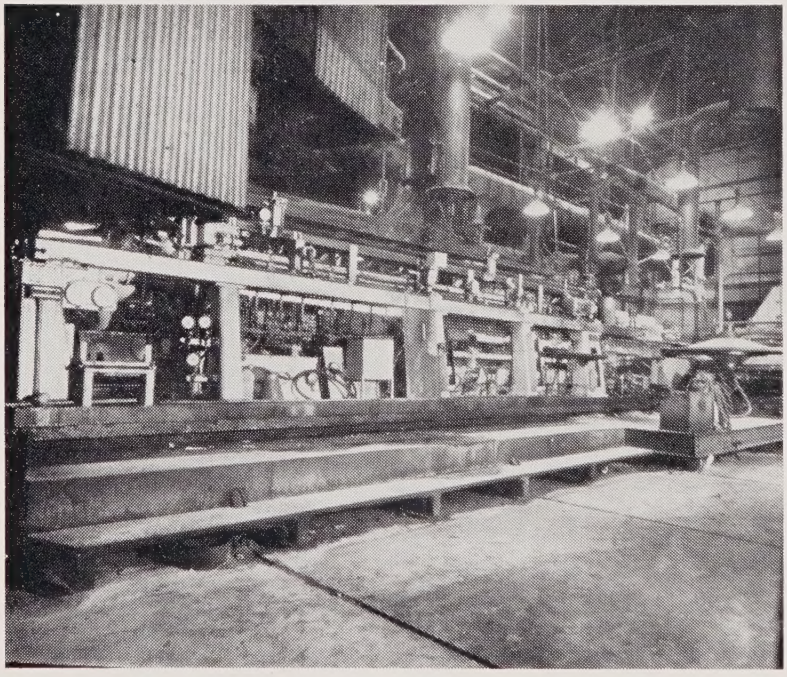
Mould open to reveal stem and half formed foot

Further Mechanization

1949:

Automatic production of stemware in the United Kingdom.

This involves the synchronization and co-ordination of machines to blow the bowl, form the stem and foot, and assemble all these parts.



Ribbon Machine

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